

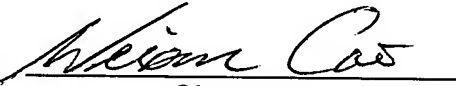
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US Utility Patent Application for

DIRECT MODULATION OF A POWER AMPLIFIER WITH ADAPTIVE DIGITAL PREDISTORTION

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DIRECT MODULATION OF A POWER AMPLIFIER WITH ADAPTIVE DIGITAL PREDISTORTION

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CROSS REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of US Provisional Application entitled "Direct Power Amplifier Modulation With Adaptive Digital Predistortion", No.: 60/404,950, filed on August 21, 2002, the content of which is hereby incorporated by reference for all purpose in its entirety.

BACKGROUND OF THE INVENTION

Field of the invention

[0002] The present invention relates generally to the field of digital wireless communications. Specifically, the present invention relates to architectures of a digitally controlled radio frequency (RF) transmitter system. More specifically, the present invention relates to transmitter architectures that can operate in different modulation standards and different frequency bands by using substantially same building blocks.

Description of the related art

[0003] The fast growing demand for mobile communication systems has created many modulation (or speed) standards involving various rates and ways devices communicate with each other. These common modulation standards, such as GSM and the third generation (3G) for mobile radio standards, have compelled transmitter designers to combine different modulation standards in one device while maintaining high linearity, high power efficiency and low cost.

[0004] Particularly, the power efficiency is of great importance to portable devices (e.g., cellular phones and palm computers) employing different modulation standards, since the power amplifier is a main determinant of battery talk time. The requirements of high linearity, high power efficiency and low cost result in a strong restriction on the implementation of a RF transmitter which must have both ultra-linearity and high power efficiency for constant and non-constant envelope modulation standards.

[0005] Conventional RF transmitter architectures follow a linear approach in which the modulation of a power amplifier is performed in a linear region. However, such an operation leads to a significant decrease in the power efficiency. In order to achieve both high linearity and high power efficiency, the power efficient non-linear switching-mode power amplifier has been used with linearization techniques.

[0006] There are at least three different linearization approaches: the Linear Amplification with Nonlinear Components (LINC) technique, the Envelope Elimination and Restoration (EER) technique and predistortion. The basic principle of LINC technique, as illustrated in FIG. 1 and described in the article "Linear Amplification using Nonlinear Components" by D.C. Cox, IEEE Trans. on Communications, Vol. COM-22, pages 1942 to 1945, December 1974, is to take an envelope modulated bandpass signal and decompose it through a signal decomposer **102** into two out-phased constant envelope signals that are respectively applied to a pair of highly nonlinear power efficient amplifiers **104** (PA1) and **106** (PA2). The outputs from the amplifiers **104** and **106** are summed through a passive combiner **108**. The major advantage of the LINC transmitter **100** is that the RF amplification is performed by two highly efficient non-linear amplifiers (e.g., class-C, D or E), each operating on constant envelope signals.

However, one of the disadvantages of this technique is the extremely tight tolerances on the matching of the two amplifier paths to achieve acceptable small out-of-band rejection. Another one of the drawbacks encountered with this technique is that the output power combiner will introduce a significant loss of power efficiency.

[0007] The Envelop Elimination and Restoration (EER) technique, as illustrated in FIG. 2 and described in the article "Single-sideband transmission by envelope elimination and restoration" by Leonard. R. Kahn, Proceedings of the IRE, Vol. 40, pages 803 to 806, July 1952, is to apply an input RF signal to an Envelope Detector **210** to generate an amplitude-modulated signal, and a Hard Limiter **212** to generate a phase-modulated signal. Since the RF power amplifier **216** is freed from the requirement to amplify non-constant envelope signals, the amplitude-modulated signal from the Envelope Detector **210** can control the amplitude of the switching-mode power amplifier **216** through an adjustment of its bias and supply voltage via an amplitude controller **214**. As the phase-modulated signal from Hard Limiter **212** has a constant envelope, it can thus be implemented by one of the switching-mode RF power amplifier classes (e.g. Class D, E or F) that feature very high DC to RF power conversion efficiency. However, any mismatch between the analog phase and the amplitude signals must be minimized. This is difficult since the two paths include vastly different types of circuit elements, working at widely different frequencies.

[0008] Predistortion is a well-known concept where the input signal is modified in order to compensate for the distortion introduced by a power amplifier when it is operating in nonlinear mode. The basic form of a predistortion linearization scheme is shown in FIG. 3. The predistorter **320** with a function $P(V_{in})$ operates on the input signal V_{in} in such a manner that its output signal X is

distorted in a precisely complementary manner to the distortion produced by the power amplifier 322 with a transfer function $F(X)$. As a result, the output signal V_{out} is therefore, ideally, an amplified, but undistorted replica of the input signal with a transfer function $F(P(V_{in}))$. The task of the adaptive predistortion is to adaptively predistort the input samples in order to minimize the errors. The switching-mode power amplifier has inherent non-linearities associated with them. These non-linearities are due to the fact that the amplifier's gain and phase characteristics change with a change in the power supply voltage, and thus the signal dependent power supply voltage is a source of amplitude to amplitude (AM-AM) and amplitude to phase (AM-PM) distortion. The adaptive predistortion adjusts the modulation signal by inverse characteristic of the power amplifier. Thus, the overall response of the cascaded predistorter and power amplifier demonstrates linearity. Some experimental results and demonstrating are given in the article "Experimental Performance of an Adaptive Digital Linearized Power Amplifier" by Andrew S. Wright and Willem G. Durtler, IEEE Transactions on Vehicular Technology, Vol.41, No.4, pages 395-400, November 1992. The main advantage of the digital predistortion is its capability for wide bandwidth operation and simplicity for the implementation.

[0010] One example of direct phase modulation is to use a fractional-N frequency synthesizer 400 as illustrated in FIG. 4. But the bandwidth of the fractional-N frequency synthesizer 400 is strongly limited by its phase-locked loop formed by a divider 404, a phase detector 403, a loop filter 402 and a VCO 401. In particular, the article "A 27-mW CMOS Fractional-N Synthesizer Using Digital Compensation for 2.5-Mb/s GFSK Modulation" by Michael H. Perrott and etc., IEEE Journal of Solid-State Circuits, Vol. 32, No.12, December 1997, pages 2048 to 2060, describes a wideband fractional-N synthesizer. It requires a

compensated transmit filter which is difficult to implement, and an accurate loop filter to mitigate the mismatch problem. However, this approach is not efficient and suitable for the phase modulation with different modulation standards.

[0011] There is thus a great need for a generic RF transmitter architecture that can maximize the power efficiency with wide bandwidth and high linearity for different modulation standards at low cost.

SUMMARY OF THE INVENTION

[0012] This section is for the purpose of summarizing some aspects of the present invention and to briefly introduce some preferred embodiments. Simplifications or omissions in this section as well as in the abstract may be made to avoid obscuring the purpose of this section and the abstract. Such simplifications or omissions are not intended to limit the scope of the present invention.

[0013] The present invention pertains to a generic RF transmitter architecture using a switching-mode power amplifier to maximize the power efficiency and method therefor. According to one aspect of the present invention, RF transmitter systems employing the present invention can achieve both high power efficiency and high linearity for different modulation standards but be of low cost. The present invention may be advantageously used in the mobile devices and/or base stations (e.g., the third generation (3G) wireless communication systems and advanced satellite communication systems).

[0014] The RF transmitter architecture contemplated in the present invention provides a generic RF transmitter design platform from baseband

digital signal processing up to RF transmission signal. Some of the features, advantages and benefits are listed as below:

- high power efficiency is obtained by using switching-mode RF amplifiers;
- accurate digital predistortion of switching-mode RF amplifiers is achieved by using digital signal processing technique with separated amplitude and phase demodulated feedback paths;
- a desired signal is generated directly at RF without requiring intermediate frequency (IF) and up-conversion mixer and costly band pass filter;
- an instantaneous wideband modulated frequency is directly manipulated by using feed forward phase modulation technique combined with a phase-locked loop;
- different modulation standards and different frequency bands are accommodated;
- high performance linear modulation of RF signals with low output noise power, spurious levels and current consumption are achieved; and
- the costly Surface Acoustic Wave (S.A.W) filters traditionally used in conventional digital radio transmitter architectures are eliminated.

[0015] The present invention may be implemented in numerous ways. According to one embodiment, the present invention is a transmitter operating in a switching-mode, the transmitter comprises a signal decomposition unit decomposing a modulated digital signal into a first signal (amplitude) and a second signal (phase), both being expressed in polar coordinates mathematically; an adaptive predistorter distorting the first and second signals respectively in accordance with one or more of distorting parameters; a phase equalizer equalizing a time delay between the first and second signals in

response to a measurement provided by a feedback loop operating on a sample of a RF signal from the transmitter; and a power amplifier, controlled by the first signal and a control signal from a voltage controlled oscillator, producing the RF signal, wherein the control signal is derived from the second signal.

[0016] According to another embodiment, the present invention is a method for controlling a transmitter to operate in a switching-mode, the method comprises decomposing a modulated digital signal into a first signal (e.g., amplitude) and a second signal (e.g., phase), both being expressed in polar coordinates mathematically; distorting the first and second signals respectively in accordance with one or more of distorting parameters; equalizing a time delay between the first and second signals in response to a measurement provided by a feedback loop operating on a sample of a RF signal from the transmitter; and producing the RF signal in a power amplifier controlled by the first signal and a control signal from a voltage controlled oscillator, wherein the control signal is derived from the second signal.

[0017] There are many features, benefits and advantages in the present invention. One of these is to provide a generic architecture that uses amplitude and phase information to directly modulate a switching-mode power amplifier with adaptive digital predistortion. The digital predistortion includes a demodulation feedback path to detect the amplitude and phase signals generated by the power amplifier and the voltage-controlled oscillator, and adaptively correct the non-linear effects of the switching-mode power amplifier and the voltage-controlled oscillator. The timing mismatch between the amplitude and phase signals is also adaptively compensated by using digital predistortion.

[0018] Another one of the features, benefits and advantages is to provide a wideband phase modulation architecture using the direct modulation of a VCO with a fractional-N frequency synthesizer. It eliminates the intermediate frequency (IF) up-conversion mixer and costly band pass filters for conventional transmitter chains. The VCO drift, temperature variations and other nonlinear effects of a power amplifier are compensated by using digital predistortion with adaptive phase offset and gain control techniques.

[0019] Other objects, features, benefits and advantages, together with the foregoing, are attained in the exercise of the invention in the following description and resulting in the embodiment illustrated in the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0020] These and other features, aspects, and advantages of the present invention will be better understood with regard to the following description, appended claims, and accompanying drawings where:

[0021] FIG. 1 is a block diagram of a basic LINC power amplifier modulator realization;

[0022] FIG. 2 is a block diagram of the Envelope Elimination and Restoration (EER) scheme for power amplifier modulation;

[0023] FIG. 3 is a block diagram of a predistortion linearization technique for power amplifiers;

[0024] FIG. 4 is a block diagram of a conventional fractional-N phase-locked loop frequency synthesizer;

[0025] FIG. 5 is a block diagram of a transmitter architecture using direct modulation of a power amplifier with adaptive digital predistortion in accordance with one embodiment of the present invention; and

[0026] FIG. 6 shows a flowchart or process of generating a RF signal in accordance with one embodiment of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0027] The present invention pertains to a generic RF transmitter architecture using a switching-mode power amplifier to maximize the power efficiency and method therefor. According to one aspect of the present invention, a transmitter design architecture is provided to use amplitude and phase information to directly modulate a switching-mode power amplifier with adaptive digital predistortion. The digital predistortion includes a demodulation feedback path to detect the amplitude and phase signals generated by the power amplifier, and adaptively correct the non-linear effects of the switching-mode power amplifier. The timing mismatch between the amplitude and phase signals is also adaptively compensated by using digital predistortion.

[0028] The detailed description of the present invention is presented largely in terms of functional blocks, procedures, logic blocks, processing, or other symbolic representations that directly or indirectly resemble the operations of a RF transmitter that can be used in wireless communications. These descriptions and representations are typically used by those skilled in the art to most effectively convey the substance of their work to others skilled in the art.

[0029] Reference herein to “one embodiment” or “an embodiment” means that a particular feature, structure, or characteristic described in connection with

the embodiment can be included in at least one embodiment of the invention. The appearances of the phrase “in one embodiment” in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments mutually exclusive of other embodiments.

[0030] Referring now to the drawings, in which like numerals refer to like parts throughout the several views. FIG. 5 illustrates a functional block diagram of part of a transmitter **580** that may be employed in a base station or a mobile device. For example, a base station controls radio or telecommunication links with the mobile devices that include, but may not be limited to, cellular phones, mobile computing devices and laptop computers.

[0031] A baseband processor **501** provides three signals, D_{in} , f_{ref} and a carrier frequency. D_{in} or $D_{in}(t)$ is a modulated digital signal and coupled to a polar decomposition **503** to generate a phase-modulated signal PM, and an amplitude-modulated signal AM. The two modulated output signals AM and PM are then provided to an adaptive predistorter **505**. To better describe the adaptive predistorter **505**, it is assumed that the input baseband signal $D_{in}(t)$ can be expressed as rectangular modulated signals $I(t)$ and $Q(t)$ as follows:

$$D_{in}(t) = I(t) + j Q(t)$$

$D_{in}(t)$ can be also represented in polar coordinates after the polar decomposition **503** as:

$$D_{in}(t) = AM(t) \bullet e^{j PM(t)}$$

where the amplitude signal $AM(t) = [I(t)^2 + Q(t)^2]^{1/2}$ and the phase signal $PM(t) = \tan^{-1} [Q(t)/I(t)]$.

[0032] According to one embodiment, the adaptive predistorter **505** is designed by using a digital predistortion technique to compensate the AM-AM

and AM-PM distortions that may be introduced in a switching-mode power amplifier. In operation, the adaptive predistorter **505** receives the polar decomposed AM and PM signals from the polar decomposition **503** and the control signal from the predistortion calibration **533** to generate the predistorted amplitude signal AM1 and phase signal PM1 both of which are applied to the phase equalizer **507**. The parameters of the adaptive predistortion **505** are updated by the predistortion calibration **533** that calibrates feedback signals from the output of the power amplifier **529** through the demodulation **535**. In other words, the outputs of the power amplifier **529** and the voltage-controlled oscillator **521** are sampled, down-converted in the down conversion **537**, and demodulated in the demodulation **535** to facilitate the predistortion calibration **533** to update the parameters of the adaptive predistortion **505** such that the adaptive predistortion **505** distorts the polar decomposed AM and PM signals objectively or in a desirable way. Depending on implementation, the parameters of the adaptive predistortion **505** may pertain to those of components or are stored in a look-up-table.

[0033] As the power amplifier **529** operates in the nonlinear switching-mode, the phase modulation path and the amplitude modulation path can be individually adjusted by using the digital predistortion techniques. The outputs of the adaptive predistortion **505** can be described as:

$$AM1(t) = P_{am-am}(AM(t)) \quad \text{and} \quad PM1(t) = P_{am-pm}(PM(t)),$$

where $P_{am-am}(x)$ and $P_{am-pm}(x)$ are the predistortion functions for AM-AM and AM-PM distortion, respectively.

[0034] The phase equalizer **507** is used to equalize a time delay between the phase-modulation path and the amplitude-modulation path, if there is any. In operation, the phase equalizer **507** receives a feedback control signal from the

predistortion calibration **533** to adjust the time delay (difference) between the two output signals which are the amplitude-modulated signal AM2 and the phase-modulated signal PM2. The amplitude signal AM2 is coupled to the bias and supply voltage control **509** that controls the supply voltage of the switching-mode power amplifier **529**. The phase signal PM2 is applied to the phase gain **511** that uses a gain control signal produced by the predistortion calibration **533** to control the scaling factor of the received phase signal PM2. The digital output of the phase gain **511** is converted to an analog signal by a digital-to-analog (D/A) converter **513**. The output of the digital-to-analog converter **513** is added to an adder **519** to direct modulate VCO **521** in the fractional-N PLL modulation **500**.

[0035] At the same time, the phase signal PM2 is also applied to the phase offset **523** for the fractional-N PLL modulation **500** that is used to track the carrier frequency of VCO **521**. In operation, a modulated signal from the loop filter **517** is coupled to the adder **519** such that the VCO **521** operates with two signals. By using the feed-forward phase modulation through the D/A converter **513**, a change in the phase gain value will result in an equivalent change in the modulation gain of VCO **521**. Thus, the nonlinear effect of VCO gain drift can be adaptively compensated by predistorting the scaling value of the phase gain **511**.

[0036] As shown in the figure, the phase offset **523** uses a phase offset control signal produced by the predistortion calibration **533** to adjust the phase value of the phase signal PM2. The phase offset **523** adaptively compensates the carrier frequency drift due to the signal mismatch between the direct modulation path through the D/A converter **513** and the fractional-N PLL modulation path through the loop filter **517**. The output of the phase offset **523** is applied to the phase data input of the fractional-N PLL modulation **500**. The digital carrier frequency data is applied to the fractional-N PLL modulation **500** to

produce the RF carrier frequency without using the traditional up-conversion mixer.

[0037] According to one embodiment, the fractional-N phase-locked loop (PLL) frequency synthesizer **500** is used as a functional building block in the transmitter **580**. The phase-locked loop **500** includes a phase detector **515**, a loop filter **517**, a voltage controlled oscillator (VCO) **521** and a loop divider **525**. The phase detector **515** serves as a comparator means for comparing the reference signal f_{ref} to the divided loop output signal which is coupled to the output of the divider **525**. The phase detector **515** generates a frequency tuning control signal that is coupled to the loop filter **517**. The voltage level of this frequency tuning control signal is proportional to the difference in frequencies of the compared signals. The loop filter **517** receives and filters the frequency tuning control signal and provides a control signal to the input node **519** to the VCO **521**. The VCO **521** serves as a frequency generation means for generating the loop output signal f_{out} in response to the VCO input control signal. The loop divider **525** is coupled to the output of the VCO **521** and generates a divided loop signal which corresponds to the frequency to the loop output signal divided by integer N or N+1. The output of the loop divider **525** is provided as the loop feedback signal to the other input of phase detector **515**.

[0038] Referring now back to FIG. 4, a baseband digital data D_{in} is provided to the transmit filter **407** to generate a modulated data stream with smooth transition. The output of the transmit filter **407** is added to a carrier frequency, $Freq_Carrier$. The output of an adder **406** is provided to a sigma-delta modulator (DSM) **405** whose output changes the divide ratio of the PLL. Thus, a spurious free output signal is obtained by dithering the division ratio. The delta-

sigma modulator **405** and the loop divider **504** comprise a fractional-*N* divider which is used in the feedback path of the PLL **400**.

[0039] As a result of this approach, the desired baseband digital signal with phase information can be generated directly at the required radio frequency with no intermediate frequency (IF) conversion stages. The fraction-*N* division frequency synthesizer approach allows fine output frequency resolution, and reduces the overall phase noise. However, one significant drawback of the fractional-*N* frequency synthesizer is that the modulation bandwidth must be less than the PLL bandwidth. This constraint imposes a severe conflict between achieving high data rates and good noise performance. The high data rates require a wide PLL bandwidth, but low output noise requires a low PLL bandwidth in order to properly attenuate the sigma-delta quantization noise. Thus, the fractional-*N* PLL as shown in FIG. 4 is difficult to track rapid changes in the phase-modulated input signal. It is also difficult to accurately control the delay time of the modulated phase signal due to the variable delay time of the data processing paths from the input through the transmitter filter **407** and the sigma-delta modulator **405**. It can be appreciated that these problems can be readily solved by the architecture **580** of FIG. 5.

[0040] Referring to FIG. 5, there are in fact two phase modulation paths: one is the feed-forward modulation path through the phase gain **511** and the other is the fractional-*N* PLL modulation path through the phase offset **523**. These two paths are adaptively controlled by the predistortion calibration **533** to have the same gain performance for the phase modulation by monitoring the output frequency of VCO **521**. The fraction-*N* PLL **500** provides a tuning voltage through the loop filter **517** to the VCO **521** to track the carrier frequency. The feed-forward modulation path provides a tuning voltage through the D/A

converter **513** to the VCO **521** as well to produce a phase-modulated frequency. These two tuning voltages are summed together by the adder **519** to generate the final tuning voltage applied to the VCO **521**.

[0041] As the fractional-N PLL **500** is applied to track the carrier frequency without passing the modulation signal into the loop filter **517**, it can be implemented using a narrow loop bandwidth. The wide bandwidth phase-modulated signal is directly up-converted to the RF signal by directly modulating the VCO **521** through the D/A converter **513**. Thus, both wide bandwidth and low output noise for a phase modulation can be achieved.

[0042] The predistortion calibration **533** produces the control signals for the adaptive digital predistortion by comparing the digital baseband phase-modulated signal PM and amplitude-modulated signal AM to the demodulated feedback signals labeled respectively as AM_q, PM_q and PM_vco generated from the demodulation **535**. The comparing results are used to produce the predistortion control signals to update the parameters for the adaptive predistorter **505**, the phase equalizer **507**, the phase offset **523** and the phase gain **511**.

[0043] The demodulation **535** translates the down-converted signals produced by the down-conversion **537** to the baseband digital signals. The demodulated output signal AM_q represents the amplitude value of the output of the power amplifier **529**. The demodulated output signal PM_q represents the phase value of the output of the power amplifier **529**. The demodulated output signal PM_vco represents the frequency value produced by the VCO **521**. The amplitude information of the output of power amplifier **529** can be translated to a baseband digital signal AM_q by using an envelope detector. The phase

information of the outputs of the power amplifier **529** and the VCO **521** can be translated to a baseband digital signal PM_q and PM_{vco} by using a hard limiter and a frequency-to-digital converter.

[0044] The down-conversion **537** converts the output of the power amplifier **529** and the output F_{out} of the VCO **521** from RF frequency down to a low intermediate frequency (IF) within a sampling range from DC up to 100 MHz. The down-converted signals are applied to the input of Demodulator **535** for demodulation processing.

[0045] Referring now to FIG. 6, there shows a flowchart or process **600** of generating a RF signal in accordance with one embodiment of the present invention. The process **600** may be implemented in hardware or a combination of hardware and software as a system, an apparatus or a method. FIG. 580 shows one exemplary implementation of the process **600**. The process **600** may be understood in conjunction with FIG. 5.

[0046] At **602**, the process **600** awaits a modulated digital signal and only proceeds when the modulated digital signal is received (e.g., from a baseband processor). At **604**, the received modulated digital signal is split into two signal components (e.g., amplitude and phase) that are expressed in polar coordinates. These two signals are then respectively predistorted in accordance with a set of distortion parameters at **606**. As described above, the distortion parameters are updated, adjusted or corrected by a feedback loop operating on a sample of the final RF signals.

[0047] At **608**, the two predistorted signals are equalized with respect to one or more common parameters. As the two signals eventually go through two different paths to control a **switching-mode** power amplifier and result in a time

shift, as shown in FIG. 5, a time delay between the two predistorted signals are equalized to compensate for such time shift. Accordingly, the one or more common parameters that are used at **608** are also updated, adjusted or corrected by the feedback loop operating on a sample of the final RF signals.

[0048] As a result of **608**, there are two signals, referred to as a first signal and a second signal. The first signal (e.g., an amplitude) is used to control the power amplifier that subsequently generates the RF at **614**. In one embodiment, the first signal drives bias and supply voltage to control the power amplifier. The second signal (phase) is provided to two phase modulation paths at **610** and **612**. At **610**, a feed-forward modulation path operates on the second signal through a phase gain unit. At **612**, a fractional-N PLL modulation path operates on the second signal through a phase offset unit. Not shown in FIG. 6, these two paths are adaptively controlled by the feedback loop operating on a sample of the final RF signals. The outputs of the two paths are combined to control the voltage controlled oscillator that in turn generates the phase-modulated signal to the input of the power amplifier.

[0049] At **616**, the outputs from the power amplifier and the voltage controlled oscillator are sampled and used to facilitate the feedback loop to update, adjust or correct all the parameters to process the aforementioned two signals as well as the two modulation paths.

[0050] The process **600** of FIG. 6 is simple in implementation in view of the functional block diagrams in FIG. 5 as most of the functional blocks can be implemented with digital circuitry, instead of sensitive analog circuitry. All digital signal processing circuitry can be easily reconfigured for the applications with

different modulation standards. The process **600** can achieve high efficiency and low noise for the implementation of a RF transmitter.

[0051] The present invention has been described in sufficient detail with a certain degree of particularity. It is understood to those skilled in the art that the present disclosure of embodiments has been made by way of examples only and that numerous changes in the arrangement and combination of parts may be resorted without departing from the spirit and scope of the invention as claimed. Accordingly, the scope of the present invention is defined by the appended claims rather than the forgoing description of embodiments.